The Science Fiction of Artificial Gravity

Workshop on Revolutionary Aerospace Systems Concepts for Human/Robotic Exploration of the Solar System

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Prolonged 0-Gravity is devastating

- Bone- and tooth-loss
  - calcium excretion
- Cardiovascular problems
  - muscle atrophy
- Neurovestibular dysfunction
  - orientation, posture control
- Immune deficiency

Traditional countermeasures are inadequate for long-duration space flight

- Exercise and electrical muscle stimulation
- LBNP
- Diet and drugs (e.g. to prevent calcium excretion)
- Pre-flight training

Artificial Gravity is indispensable

- AG is the only countermeasure that removes the cause for deconditioning
- A 3-year mission without AG would be unethical
- AG research is sadly underdeveloped
- AG has sensory side-effects to which humans have to adapt
- Limits to this adaptability pose serious constraints on the implementation of AG

Major Features of Rotating Environments

Artificial Gravity Level (Centripetal Accel.)

$r\omega^2$

Coriolis Forces

$-2m(\omega \times v)$

Gravity Gradients

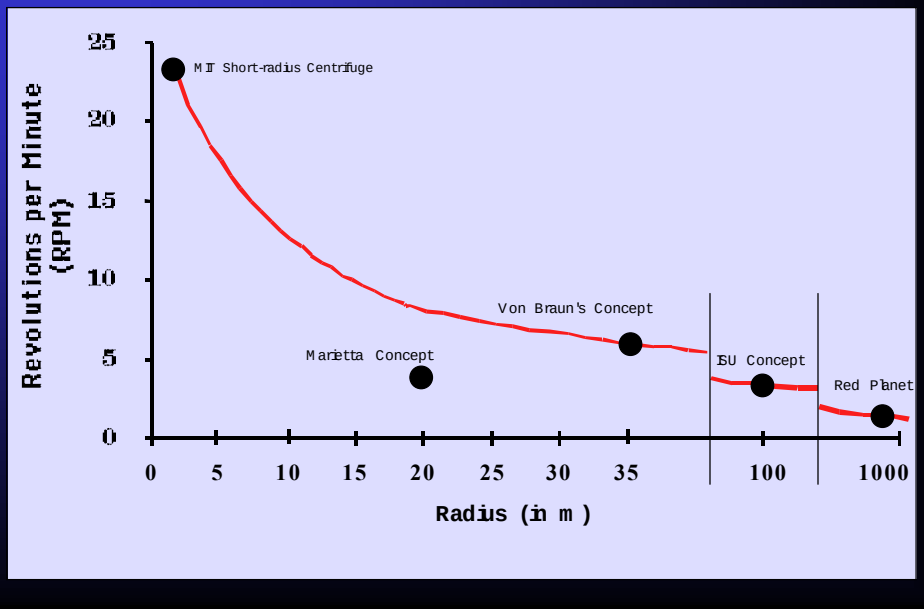
h/r

Cross-coupled Angular Accelerations

$\omega_{SRC} \times \omega_{Head}$

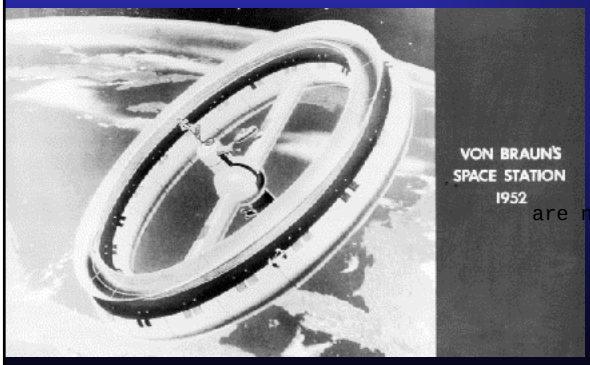
Artificial Gravity Level Tradeoff

1.0 g - boundary



Long-Radius Centrifugation

- Forgone conclusion in most science fiction scenarios of space travel



QuickTime™ and a
decompressor
are needed to see this picture.

Red Planet

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Long-Radius Designs

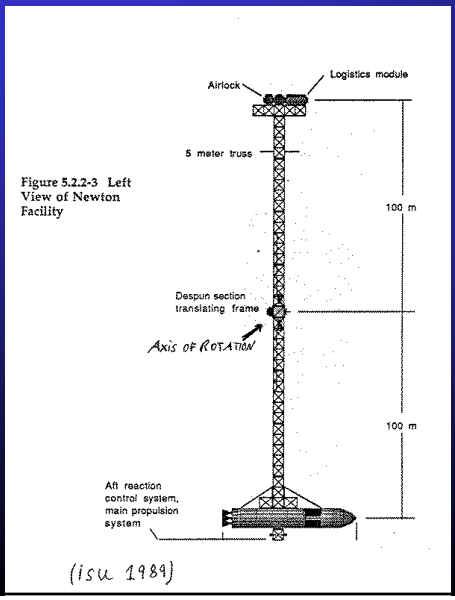
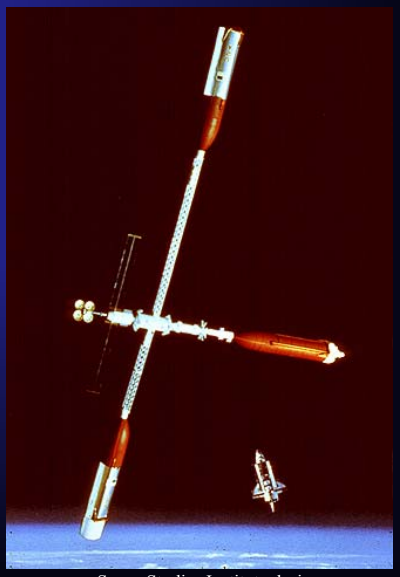


Figure 5.2.2-3 Left View of Newton Facility



Space Studies Institute design

Short-Radius Centrifugation

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decompressor
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Irvine Space Cycle
(1st and 2nd generation)

QuickTime™ and a
decompressor
are needed to see this picture.

Centrifugation Side-Effects

–Inappropriate non-compensatory nystagmus
–Motion sickness
–Illusory tilt sensations
–Orientation problems
–Postural instability
–Disturbance of motor actions as a function of location and orientation within the centrifuge

Mastering the Side-Effects

OPTIONS:

1. Increase radius above 300 m
2. Limit exposure to brief (1 h daily) periods
   = Intermittent centrifugation
3. Establish multiple adaptive states
   = Context-specific adaptation

Long-Radius Centrifugation

Advantages

- Earth-like conditions
- Gravity gradient insignificant
- Coriolis-effects are negligible - with sufficiently large radius
- Only 2 adaptive states required (1-g and Destination-g)

Long-Radius Centrifugation

Concerns

- Expensive
- Engineering challenges
- Difficult to turn on and off
- Coriolis-effects - when noticeable - are omnipresent

Short-Radius Centrifugation

Advantages

- Can be intermittent
- Cost-effective
- Space-efficient
- Relatively easy to implement
- Fits within almost any space craft
  (and inside Shuttle, ISS/Spacehab)
- Easy to turn on and off

Short-Radius Centrifugation

Concerns

- Multiple adaptive states required (Earth 1-g, 0-g, Artificial-g with gradient, Destination-g)
- Strong side-effects because of high rotation rates
  - Inappropriate non-compensatory nystagmus
  - Motion sickness
  - Illusory tilt sensations
  - Orientation problems
  - Postural instability

Feasibility Matrix: Radius and Exposure Duration

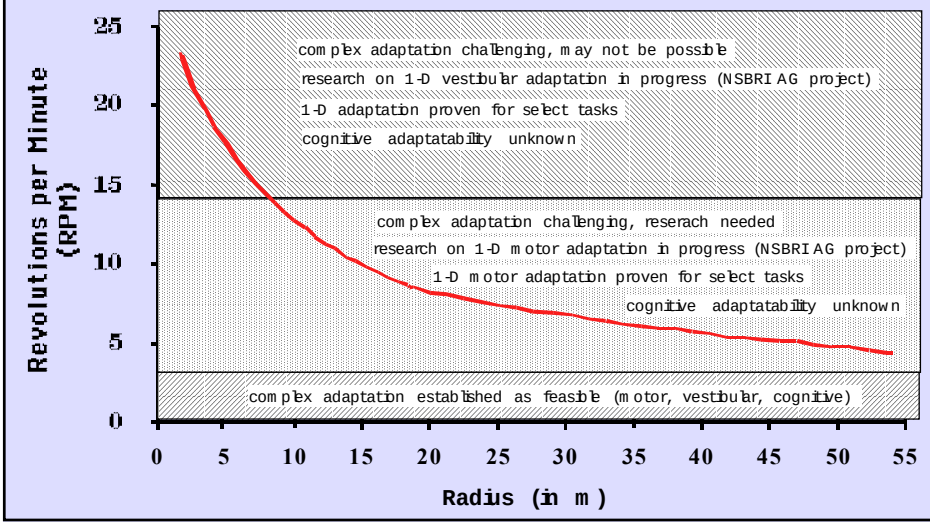
EXPOSURE \ RADIUS	short	long
intermittent	adaptation less critical 1-D adaptation may be sufficient	impractical if not impossible
continuous	adaptation most critical complex adaption to the fullest extent mandatory	complex adaptation critical but manageable due to small magnitude

Adaptability to side-effects is prime research objective

ongoing ground-based research

- –Neurovestibular side-effects of centrifugation
  - –Illusory tilt adapts
  - –VOR adapts
  - –Dual adaptation possible
- –Motion sickness can be overcome with and without drugs
- –Simple motor-coordination recalibrates

Adaptability to Artificial Gravity Side Effects



Adaptation of VOR, illusory tilt, motion sickness on MVL Short-Radius Centrifuge

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

future ground-based research

Intermittent Short-Radius Centrifugation

- –Neurovestibular: Multiple adaptation to complex head movements
- –Can complex motor-coordination recalibrate?
- –Bedrest studies to determine extent of cardiovascular and bone benefits with g-gradient
- –Optimizing dosage, radius, pre-training, etc.

flight research

- –Precious few animal studies
  - –Cosmos satellites
  - –Plans for ISS, Mars Society
- –One human study of neurovestibular Coriolis effects on Neurolab
- –No human studies with AG to this date

Operating in a permanent AG environment

- Assume the astronaut has adapted to the following
  - motion sickness
  - motor recalibration
  - neurovestibular side-effects
- Cognitive adaptation to Coriolis forces will remain a challenge

Intuitive Physics

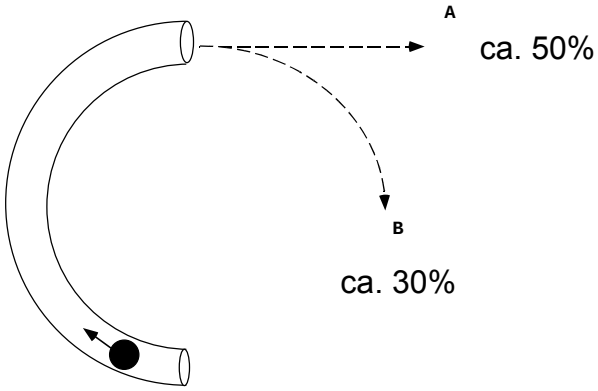
–Human intuitions about physics problems are often erroneous

–When working in a rotating environment we cannot afford to have wrong intuitions about how objects will behave

–Cognitive and perceptual implications of AG need to be investigated

The C-shaped tube problem

Production task (paper & pencil)



ca. 50%

ca. 30%

McCloskey, Caramazza & Green (1980)

C-shaped tube

QuickTime™ and a
Animation decompressor
are needed to see this picture.

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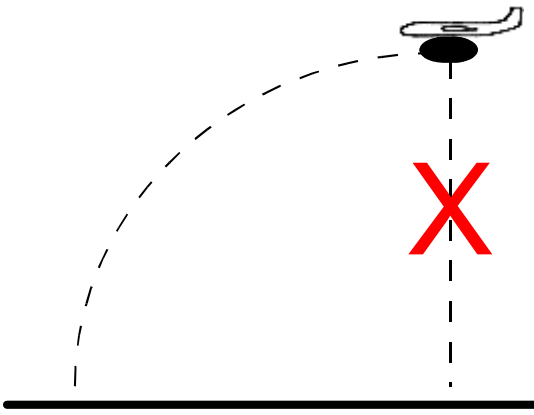
Visual animation eliminates errors on this task
(Kaiser et al., 1992)

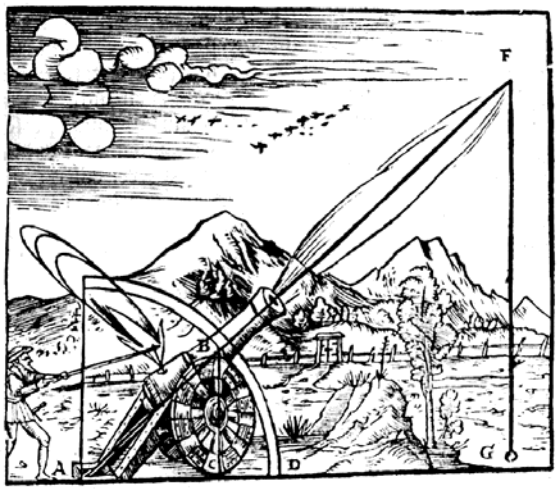
The straight-down belief



ca. 50% error in paper and pencil tasks (McCloskey et al.)

ca. 36% error with crude animation (McCloskey et al.)

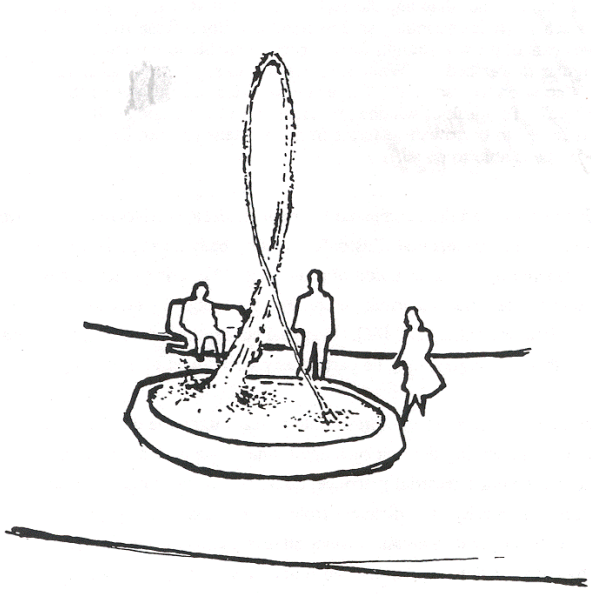
ca. 15% error with sophisti-cated animation (Kaiser et al.)



The "straight-down belief" has evolutionary roots (Illustration Daniel Santbech, Problematum Astronomicorum, Basel, 1561)

Parabola is attributed to Galileo (ca. 1600)

Better drop the straight-down belief



A fountain in artificial gravity.
(Illustration by Tye-Yan "George" Yeh.)

Intuitive Physics in a Coriolis Environment

- –Humans are likely to have serious difficulties acquiring intuitions about Coriolis forces
- –Orientation with respect to rotation plane and direction will become a new cognitive and perceptual dimension
- –We have not even started to think about the added perceptual and cognitive load that is required to function in AG

Conclusions

- AG is indispensable
- Implementation with an affordable radius causes side-effects
- Context-specific adaptability is the key to overcoming the side-effects
- Intermittent AG might get away with simple adaptation (preliminary research looks promising)
- Flight experiments are needed to assess whether intermittent AG is a sufficient countermeasure
- Continuous AG with affordable radius makes complex adaptation mandatory
- We are only starting to look at complex vestibular and motor adaptation
- Cognitive aspects of complex adaptation are terra incognita

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Acknowledgements

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